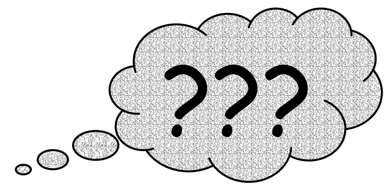
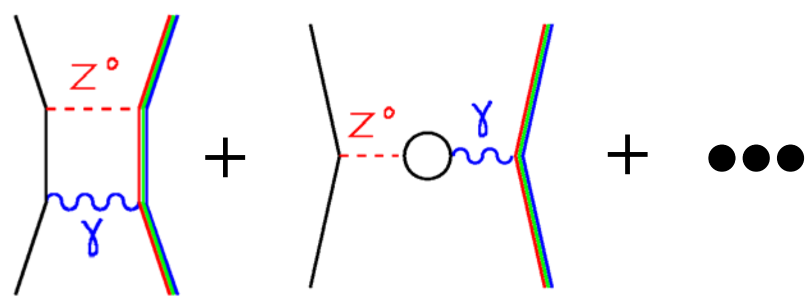
The Q^p_{Weak} Experiment: (Jefferson Lab, E02-020)

A precision search for new physics beyond the Standard Model via parity-violating e-p scattering at low Q^2

http://www.jlab.org/qweak/



Electroweak radiative corrections
$\rightarrow \sin^2\theta_W$ varies with Q



The Q_{weak} Collaboration:

18 institutions, 63 collaborators & growing....

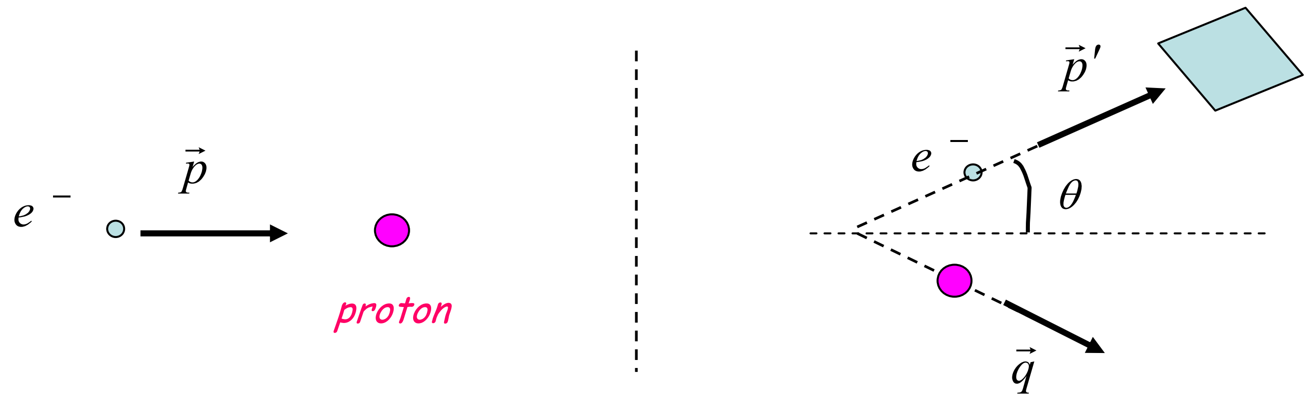
Qweak Collaboration Spokespersons

Bowman, J. David - Los Alamos National Laboratory
Carlini, Roger (Principal Investigator) - Thomas Jefferson National Accelerator Facility
Finn, J. Michael - College of William and Mary
Kowalski, Stanley - Massachusetts Institute of Technology
Page, Shelley - University of Manitoba

Qweak Collaboration Members

Armstrong, David - College of William and Mary
Averett, Todd - College of William and Mary
Birchall, James - University of Manitoba
Botto, Tancredi - Massachusetts Institute of Technology
Bruell, Antje - Thomas Jefferson National Accelerator Facility
Chattopadhyay, Swapan - Thomas Jefferson National Accelerator Facility
Davis, Charles - TRIUMF
Doornbos, J. - TRIUMF
Dow, Karen - Massachusetts Institute of Technology
Dunne, James - Mississippi State University
Ent, Rolf - Thomas Jefferson National Accelerator Facility
Erler, Jens - University of Mexico
Falk, Willie - University of Manitoba
Farkhondeh, Manouchehr - Massachusetts Institute of Technology
Forest, Tony - Louisiana Tech University
Franklin, Wilbur - Massachusetts Institute of Technology
Gaskell, David - Thomas Jefferson National Accelerator Facility
Grimm, Klaus - College of William and Mary
Hagner, Caren - Virginia Polytechnic Inst. & State Univ.
Hersman, F. W. - University of New Hampshire
Holtrop, Maurik - University of New Hampshire
Johnston, Kathleen - Louisiana Tech University
Jones, Richard - University of Connecticut
Joo, Kyungseon - University of Connecticut
Keppel, Cynthia - Hampton University
Khol, Michael - Massachusetts Institute of Technology
Korkmaz, Elie - University of Northern British Columbia
Lee, Lawrence - TRIUMF
Liang, Yongguang - Ohio University
Lung, Allison - Thomas Jefferson National Accelerator Facility
Mack, David - Thomas Jefferson National Accelerator Facility
Majewski, Stanislaw - Thomas Jefferson National Accelerator
Mammei, Juliette - Virginia Polytechnic Inst. & State Univ.
Mammei, Russell - Virginia Polytechnic Inst. & State Univ.
Mitchell, Gregory - Los Alamos National Laboratory
Mkrtchyan, Hamlet - Yerevan Physics Institute
Morgan, Norman - Virginia Polytechnic Inst. & State Univ.
Opper, Allena - Ohio University
Penttila, Seppo - Los Alamos National Laboratory
Pitt, Mark - Virginia Polytechnic Inst. & State Univ.
Poelker, B. (Matt) - Thomas Jefferson National Accelerator Facility
Porcelli, Tracy - University of Northern British Columbia
Ramsay, William - University of Manitoba
Ramsey-Musolf, Michael - California Institute of Technology
Roche, Julie - Thomas Jefferson National Accelerator Facility
Simicevic, Neven - Louisiana Tech University
Smith, Gregory - Thomas Jefferson National Accelerator Facility
Smith, Timothy - Dartmouth College
Suleiman, Riad - Massachusetts Institute of Technology
Taylor, Simon - Massachusetts Institute of Technology
Tsentalovich, Evgeni - Massachusetts Institute of Technology
van Oers, W.T.H. - University of Manitoba
Wells, Steven - Louisiana Tech University
Wilburn, W.S. - Los Alamos National Laboratory
Wood, Stephen Thomas - Jefferson National Accelerator Facility
Zhu, Hongguo - University of New Hampshire
Zorn, Carl - Thomas Jefferson National Accelerator Facility
Zwart, Townsend - Massachusetts Institute of Technology

Proton Weak Charge Tutorial (part I) :

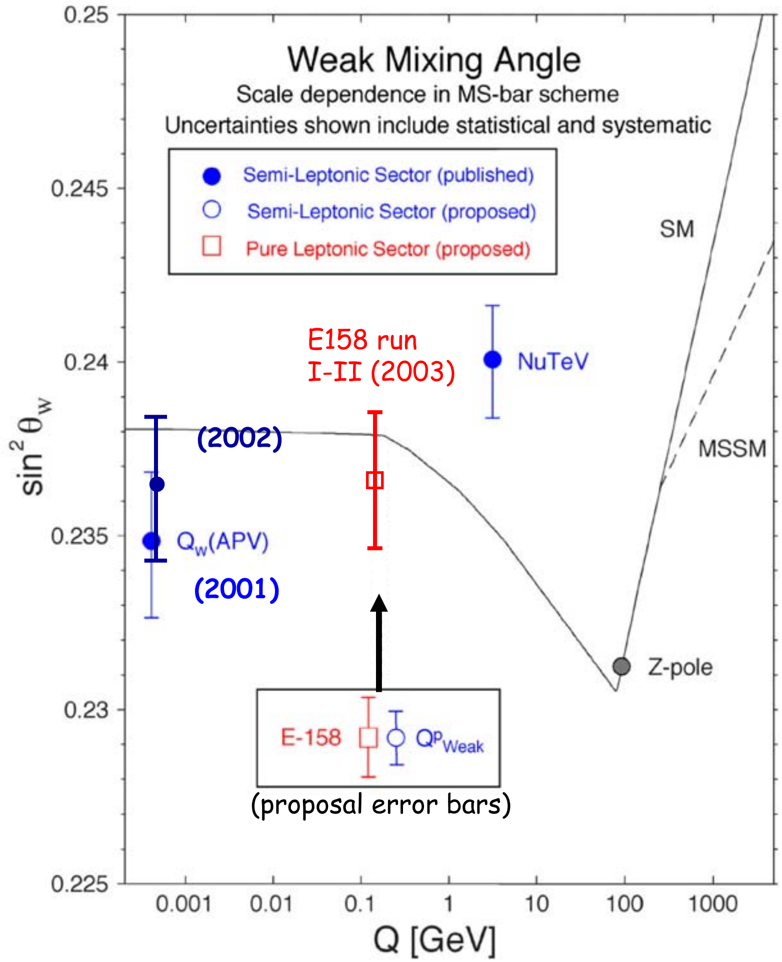


$$Q \equiv (\vec{q}, i\nu) = \left[(\vec{p} - \vec{p}\,'), i(E - E')\right]$$

- Weak proton form factors: $G^Z_E(Q^2)$ and $G^Z_M(Q^2)$ describe the electric and magnetic response as probed by the Z boson
- The $Q^2 \rightarrow 0$ limit of G^Z_E is the proton's weak charge, which we will measure at JLab:

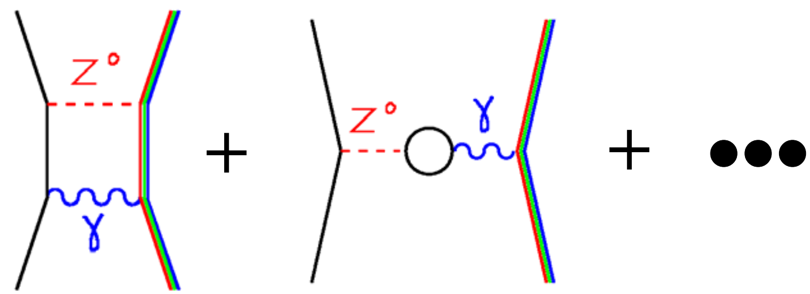
$$\boxed{Q^p_{weak} = 1 - 4\sin^2\theta_W \quad (+\ corrections...)}$$

"Running of $\sin^2\theta_W$" in the Standard Model



Erler et al., Phys. Rev D 68, 016006

Electroweak radiative corrections
$\rightarrow \sin^2\theta_W$ varies with Q

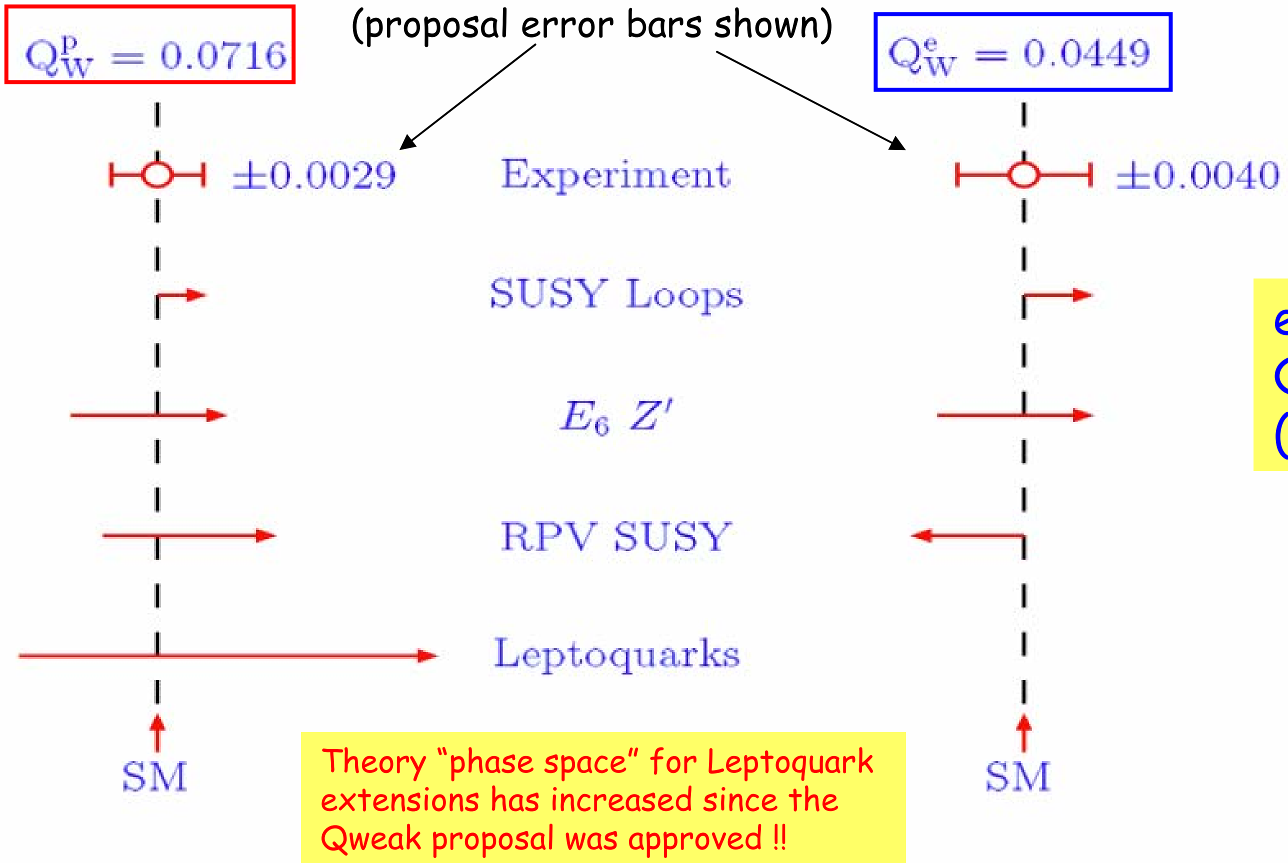


All "extracted" values of $\sin^2\theta_W$ must agree with the Standard Model prediction or new physics is indicated.

Q^p_{weak} and SLAC E158 (pure leptonic) have different sensitivities to proposed Standard Model extensions.

Sensitivity of proton and electron weak charge measurements:

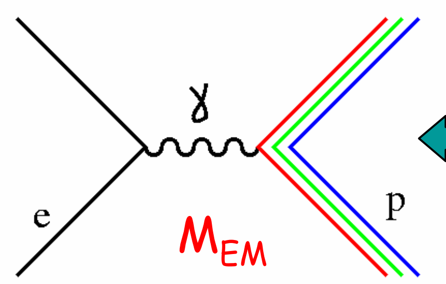
proton
Q_{weak}
(Jlab)



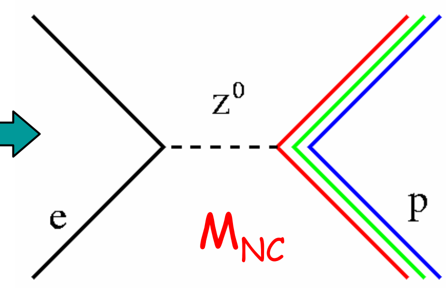
electron
Q_{weak}
(SLAC)

Comparison of anticipated errors for Qweak and E158 weak charge measurements with deviations from the Standard Model expected from various extensions and allowed (95% CL) from fits to existing data – Erler & Ramsey-Musolf.

Proton Weak Charge Tutorial: Part II



Interference gives helicity asymmetry, A, for polarized beam



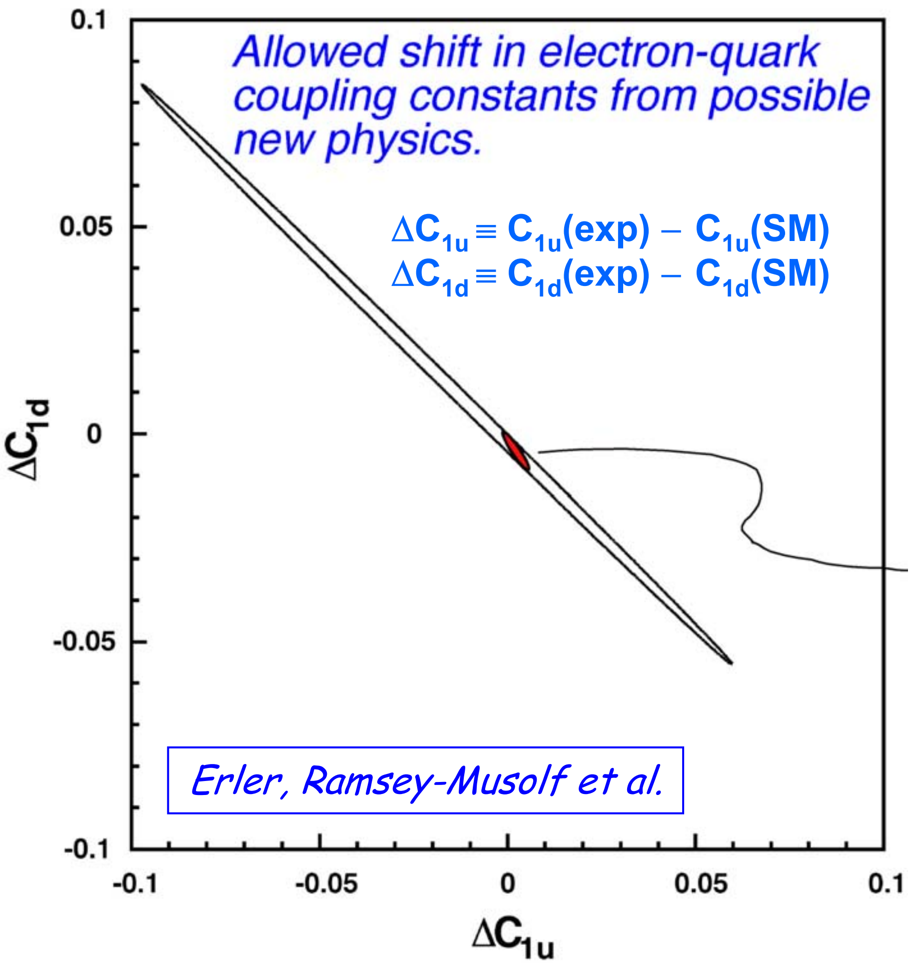
$$A = 2\frac{M_{NC}}{M_{EM}} = \frac{-G_F}{4\pi\alpha\sqrt{2}} \left(Q^2 Q^p_{weak} + F^p(Q^2,\theta) \right)$$

$$\xrightarrow{Q^2,\,\theta \to 0} \frac{-G_F}{4\pi\alpha\sqrt{2}} \left(Q^2 Q^p_{weak} + Q^4 B(Q^2) \right)$$

Aha! A measurement of the helicity asymmetry at low Q^2, plus knowledge of the hadronic form factor contribution $B(Q^2)$, allows the proton weak charge to be determined: $Q_{weak} = 1 - 4\sin^2\theta_w$.

$\delta Q_w = 4\% \rightarrow \delta\sin^2\theta_w = 0.3\%$!!!

Impact via "Model-independent Semi-Leptonic Analysis"



Effective electron-quark neutral current Lagrangian:

$$\mathbf{L}^{\text{PV}}_{\text{e-q}} = -\frac{G_F}{\sqrt{2}} \bar{e}\gamma_\mu \gamma_5 e \sum_q C_{1q} \bar{q}\gamma^\mu q$$

$$\rightarrow \text{A(e)} \quad \text{x} \quad \text{V(q)}$$

Large ellipse (existing data):
SLAC e-D (DIS)
MIT-Bates ^{12}C (elastic)
Cesium atomic parity violation

Red ellipse:
Impact of Q^p_{Weak} measurement (centroid assumes agreement with the Standard Model)

Experimental sensitivity: $Q^p_{weak} = (1 - 4\sin^2\theta_W) \cong 0.072$

Physics Asymmetry: $A(Q^2 \to 0) = -\frac{G_F}{4\pi\alpha\sqrt{2}} \left[Q^2\, Q^p_{weak} + Q^4 B\left(Q^2\right) \right]$

Precision measurement: $\boxed{\delta Q^p_W = \pm 4\% \;\Rightarrow\; \delta(\sin^2\theta_W) = \pm\; 0.3\%}$

Requirements:

1. small Q^2 (0.03 GeV^2) *(low beam energy, small angle)*
2. knowledge of hadronic form factors $B(Q^2)$ *(other expts.)*

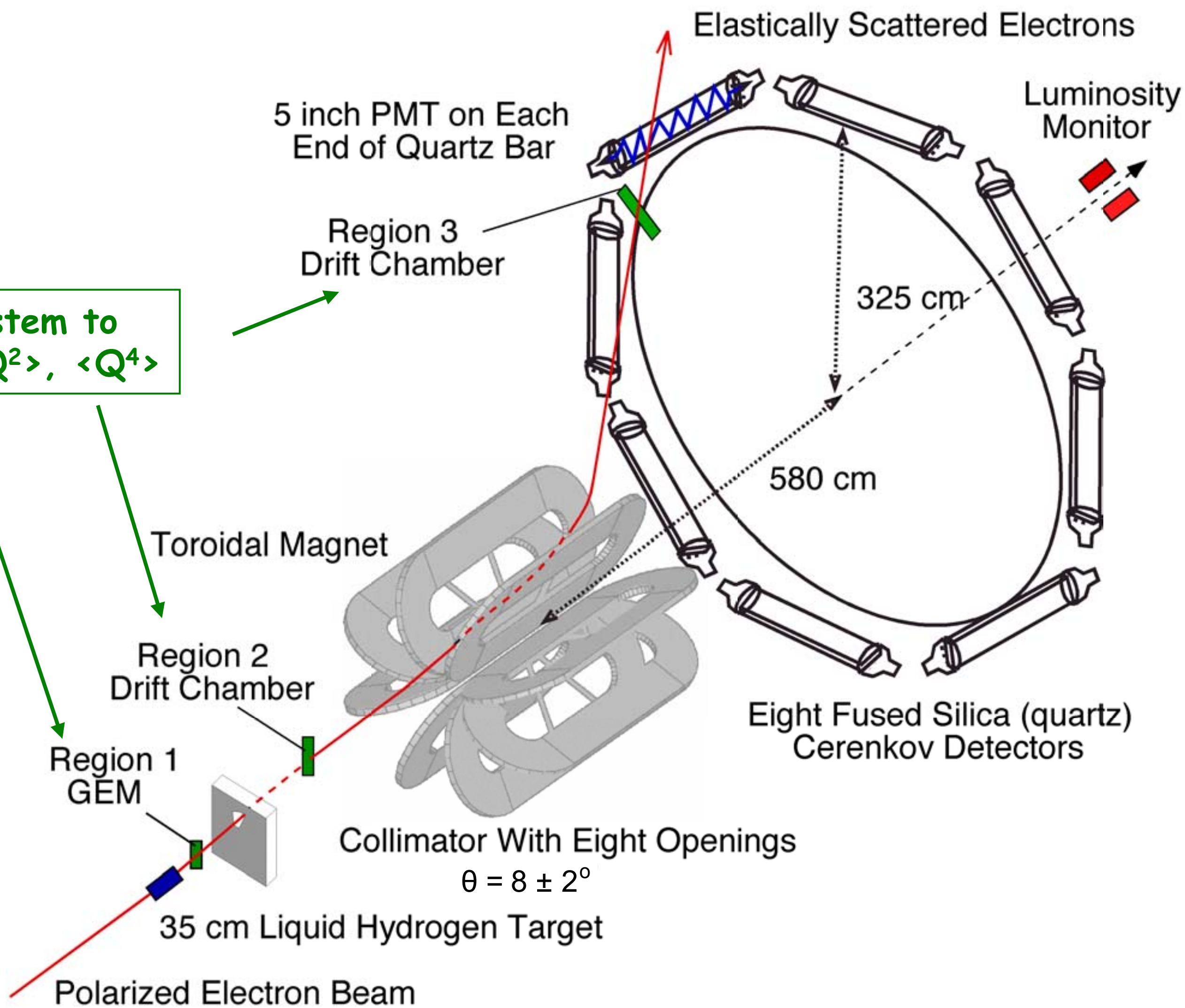
$$A\,(0.03\ \mathrm{GeV}^2) = A_{Q^p_W} + A_{hadronic} + A_{axial}$$
$$= -.19\ \mathrm{ppm} \quad -.09\ \mathrm{ppm} \quad -.01\ \mathrm{ppm}$$

3. large solid angle, integrating detector system for high sensitivity *($A \sim 10^{-7}$)*
4. highly quality polarized beam and polarimetry *(measured asymmetry is PA)*
5. measurement of detector-weighted $\langle Q^2 \rangle$ and $\langle Q^4 \rangle$
   (hybrid pulsed/integrating setup with tracking calibration)

.... etc !!!

Experimental Apparatus (schematic):

Tracking system to calibrate $\langle Q^2 \rangle$, $\langle Q^4 \rangle$



1.165 GeV, P = 0.8

Q_{weak} Experiment Parameters

Incident beam energy:	1.165 GeV
Beam Current:	180 μA
Beam Polarization:	~80%
LH_2 target power:	2.2 KW

Running Time:	Run I	23 days
	Run II	93 days

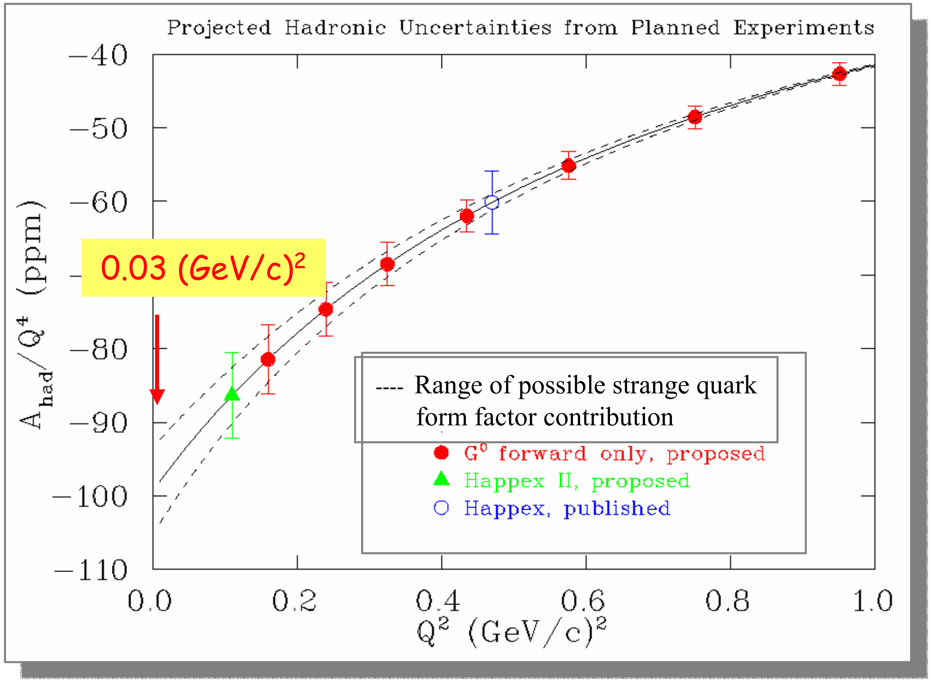
Central scattering angle:	8°
Scattering angle acceptance:	±2°
Phi Acceptance:	67% of 2π
Solid angle:	46 msr
Average Q^2:	0.03 GeV^2
Integrated Rate (all sectors):	5.6 GHz
Integrated Rate (per detector):	0.7 GHz
Acceptance averaged asymmetry:	–0.3 ppm
Statistical error per pulse pair:	5×10^{-5}

Error Budget: Total: $\Delta Q^p_{weak}/Q^p_{weak}$ = 4 %

	$\Delta Q^p_{weak}/Q^p_{weak}$		"Possible Improvements"
Statistical (2200 hours)	2.8%	→	2.5%
Systematic:			
Hadronic structure corrections $B(Q^2)$	2.0%	→	1.5%
Beam polarization	1.4%	→	1.0%
Average Q^2 determination	1.0%		
Helicity-correlated Beam Properties	0.6%		
Uncertainty in Inelastic contamination	0.2%		
Al Target window Background	<1.0%	→	0.3% (Be)
Total systematic	2.9%	→	2.2 %
Total	**4.0%**	→	**3.3%**

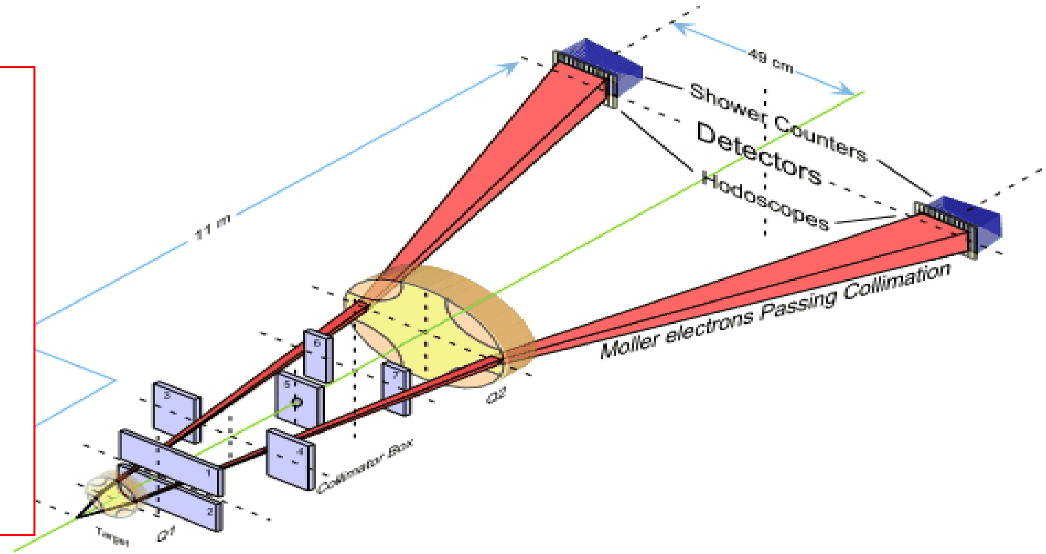
e.g. hadronic form factor extrapolation $B(Q^2)$ from other experiments:

$$\frac{\Delta Q_w}{Q_w} = \pm 2.0\%$$

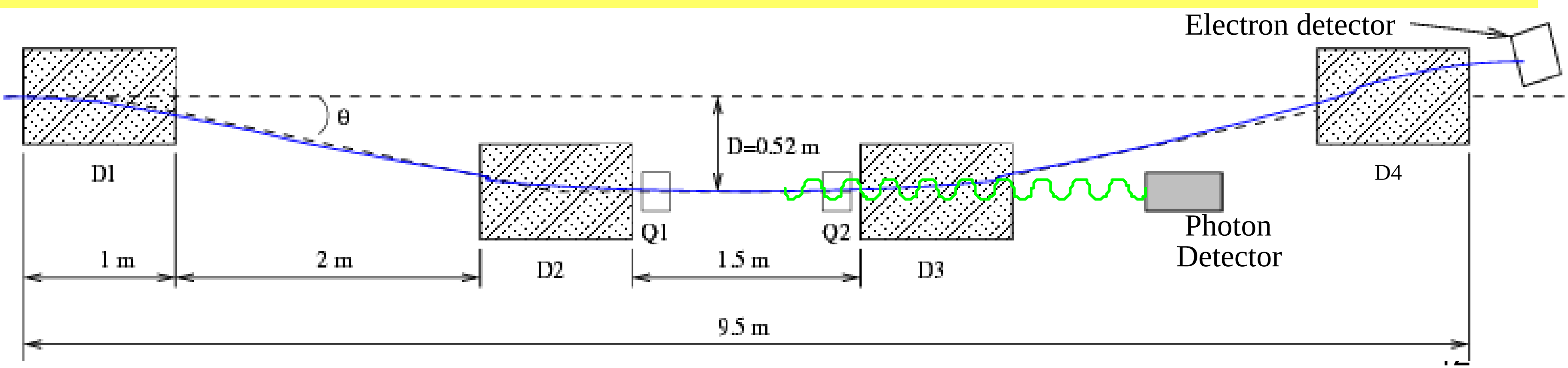


Precision Polarimetry (require ± 1%)

Existing ~ 1% Hall C Möller polarimeter -- a superconducting solenoid drives the "pure iron" target foil into saturation. The maximum operating current is I_{Max} = 2 to 10 μA , so the beam current must be reduced (and the beam retuned) to operate this polarimeter in its present configuration. Several upgrade ideas are on the table to allow effective operation at higher currents by rapid sampling.



→ A Compton Polarimeter for hall C is being developed for high current measurements



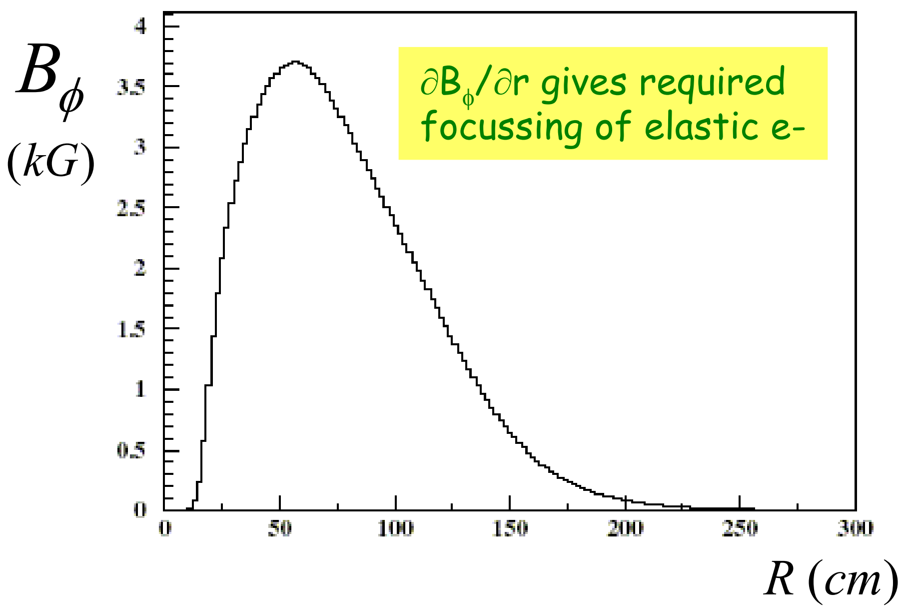
Instrumentation details: magnet

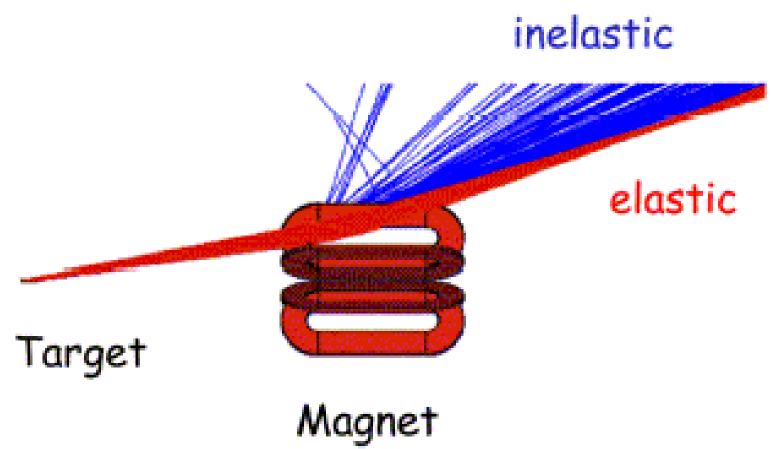
<u>Require:</u>

- symmetric, open geometry with large acceptance
- clean separation of elastic & inelastic events
- should be easy to build and maintain

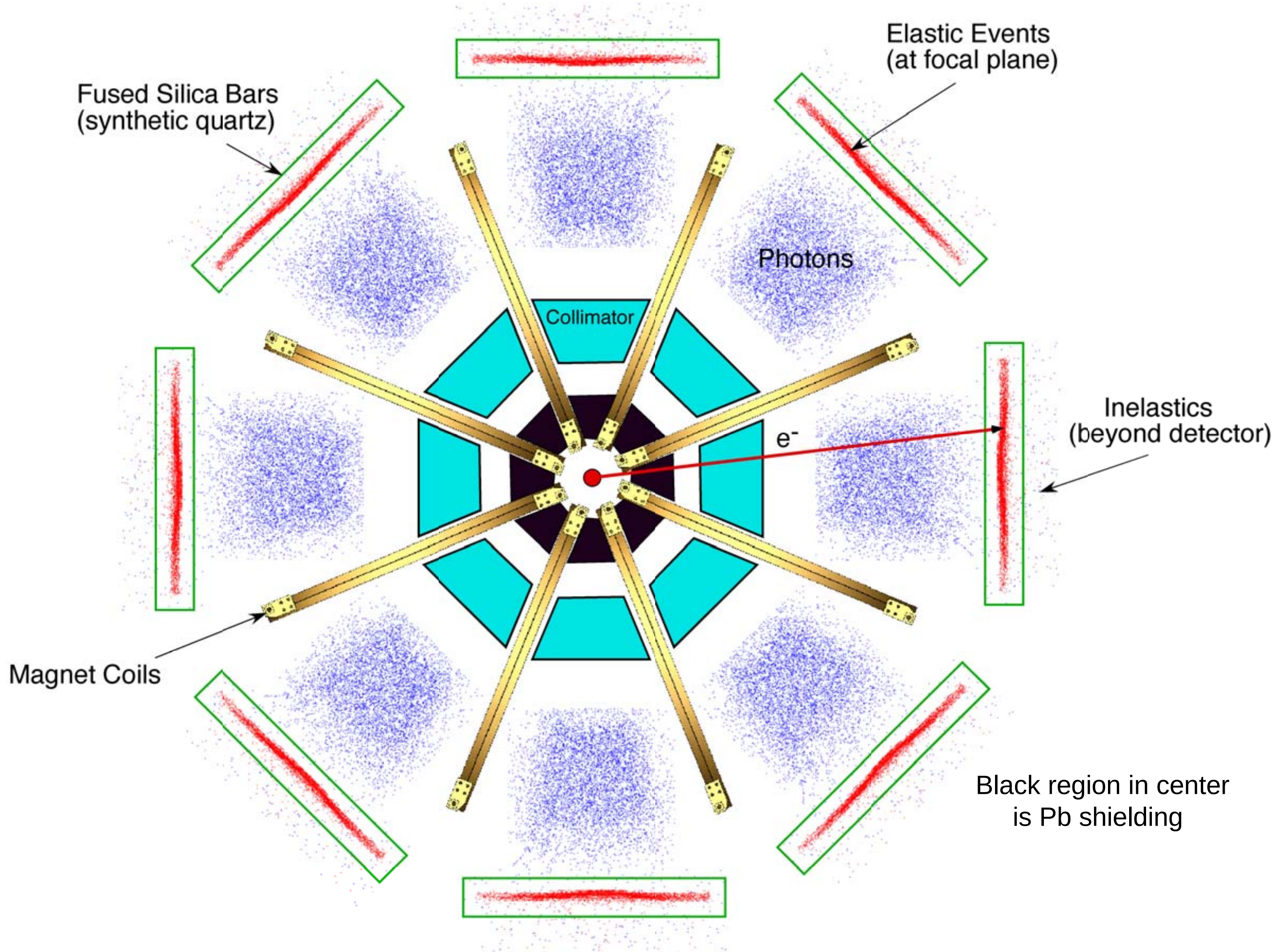
<u>Solution:</u>

- normal conducting, water-cooled toroidal spectrometer, based on the BLAST design



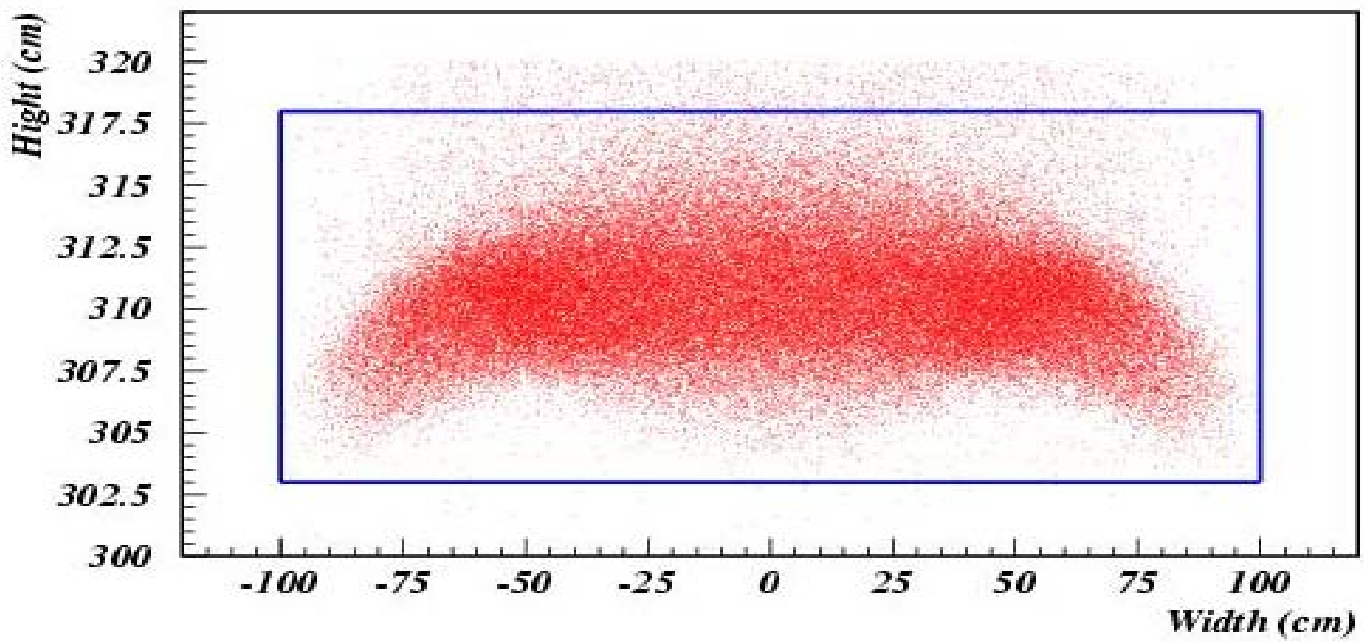


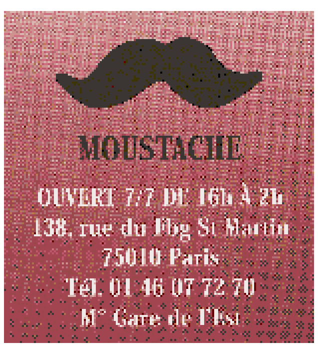
Beam's Eye View with GEANT Simulated Events



Black region in center
is Pb shielding

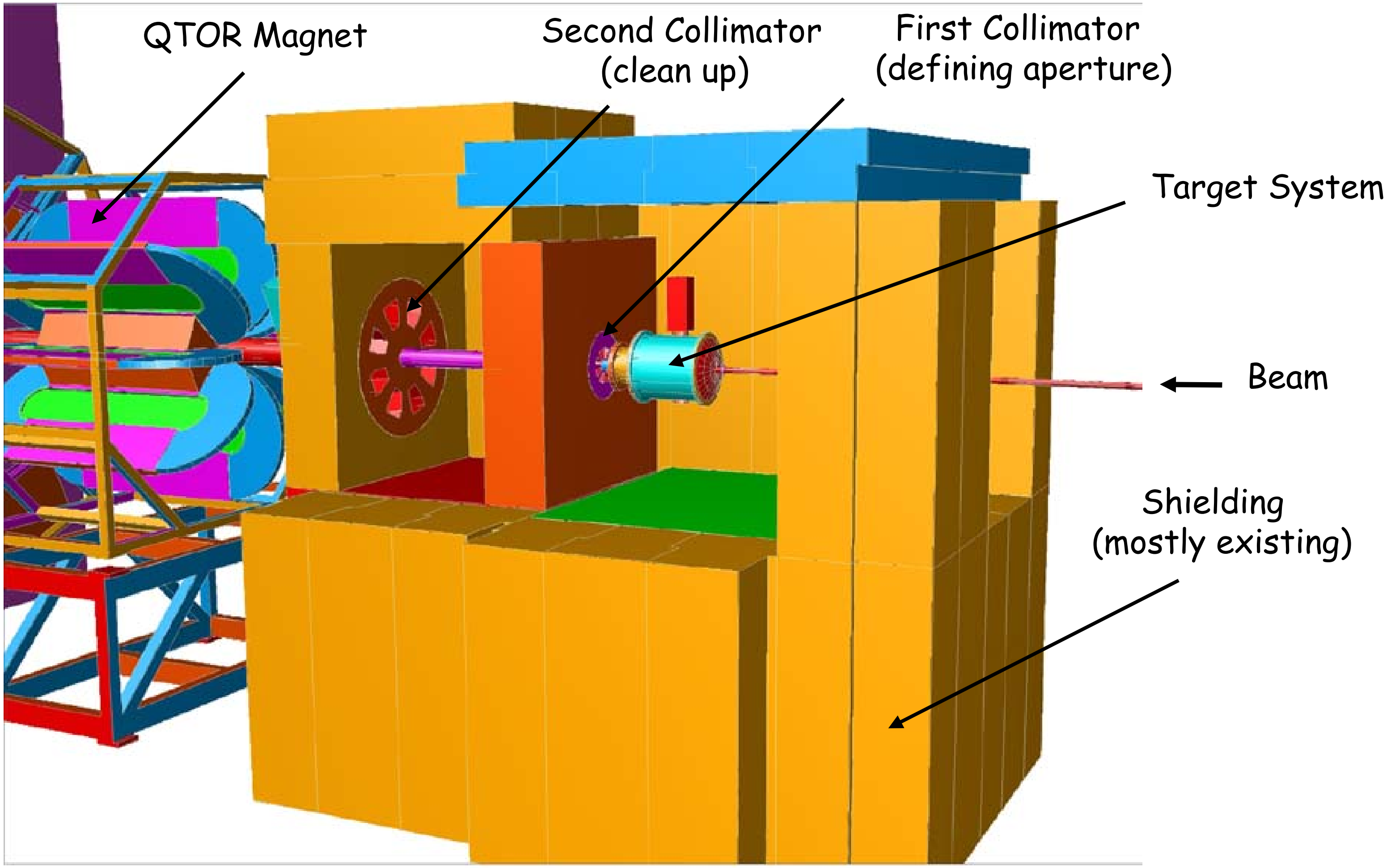
Issue: shape of elastic "moustache" on the detector bars



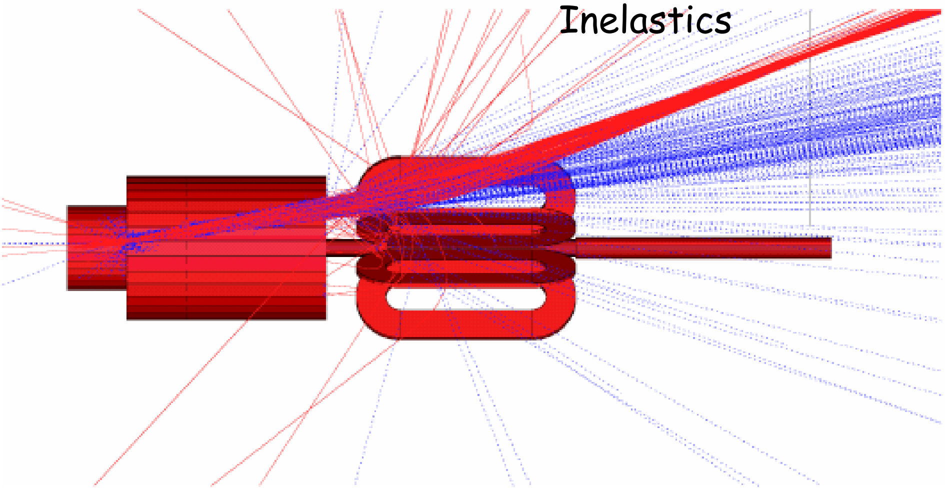


- magnet focuses in θ, defocuses in ϕ
- "moustache" ends affect sensitivity to beam motion
- collimator design is critical

CAD Illustration of Q^{p}_{Weak} Collimator System

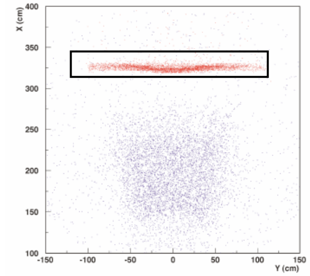


Estimate of the Inelastic & Photon Background



Elastic

Photons



GEANT simulation with double collimator.

At Detector:
(with Cerenkov cut)

Elastic e-p rate = 763 MHz / octant
Inelastic rate = 35 KHz
$\rightarrow$ Inelastic contamination ~ 0.005%

Photon rate ~ 50 KHz $\rightarrow$ Photon contamination ~ 0.007%

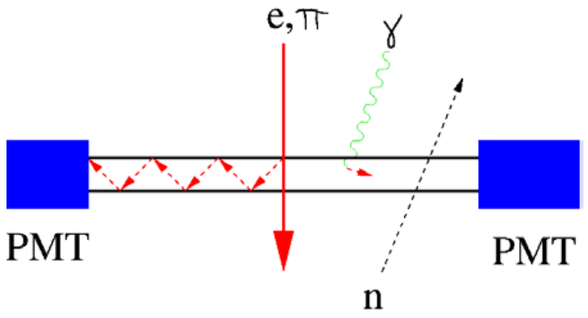
N - Δ asymmetry $A \propto 4 \sin^2\theta_W \sim 4 \times 10^{-6}$ (factor of 10 more than e-p elastic)
so the contribution of inelastic asymmetry to the elastic asymmetry ~ 0.1%

$\rightarrow$ We will also directly measure this asymmetry by running with magnet adjusted to put inelastic events on focal plane detector

The Q^p_{weak} Detector and Electronics System

Focal plane detector requirements:

- Insensitivity to background γ, n, π.
- Radiation hardness (expect > 300 kRad).
- Operation at counting statistics.

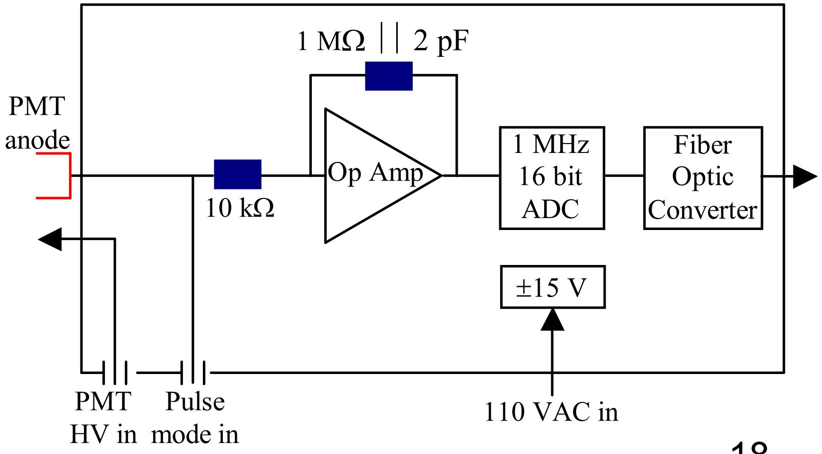


→ Fused Silica (synthetic quartz) Cerenkov detector.

- Plan to use 12 cm x 200 cm x 2.5 cm quartz bars read out at both ends by S20 photocathode PMTs (expect ~ 100 pe/event)

Electronics (TRIUMF/Manitoba/LANL):

- Normal mode: integration
- Will have option for pulse mode.
- Low electronic noise contribution. compared to counting statistics.
- 1 MHz 16 bit ADC will allow for over sampling.



Measurement of the Signal-to-Background Dilution Factor

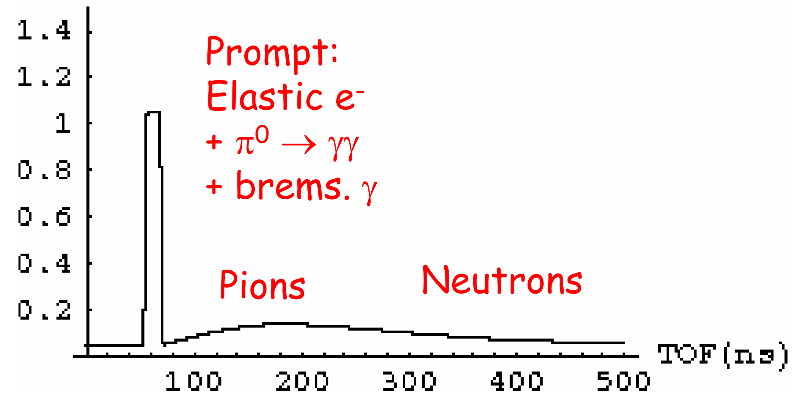
This is an integrating experiment, but we have to know how much light comes from elastic electrons!

PMT Anode $\rightarrow$
1 GHz 8 bit transient digitizer

Hybrid TOF Measurement:

- Beam: 2 MHz (instead of 499), low current
- PMT anode $\rightarrow$ 1 GHz 8 bit transient digitizer

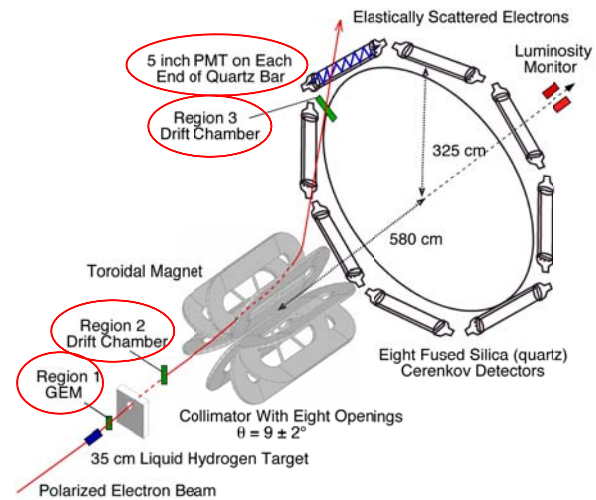
TOF distribution of the anode current
$\rightarrow$ events of interest are in the prompt peak



Decompose Prompt Peak:

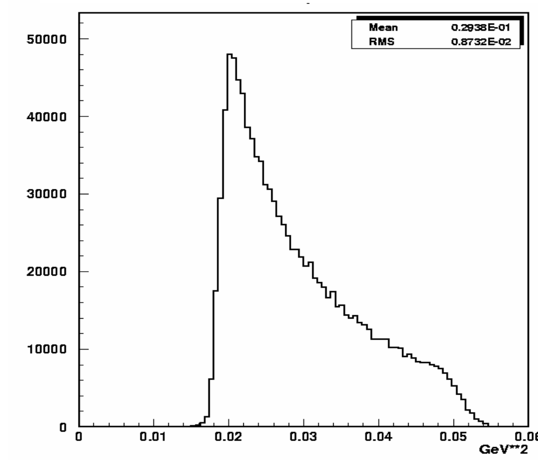
- Insert GEMs, drift chambers & scintillator.
- Run at low beam current ("pulse mode") in coincidence.

- Scintillator allows for neutral rejection.
- Tracking traces origin of scattered particles.



Determination of Average Q^2

Expected Q^2 distribution

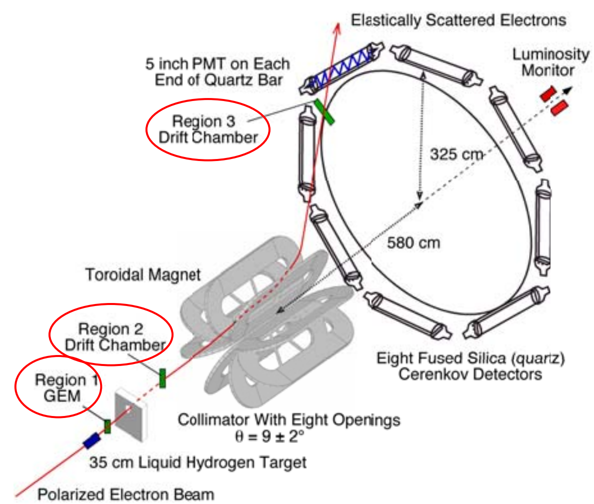


Need to know $\Delta\langle Q^2\rangle/\langle Q^2\rangle \sim 0.7\%$

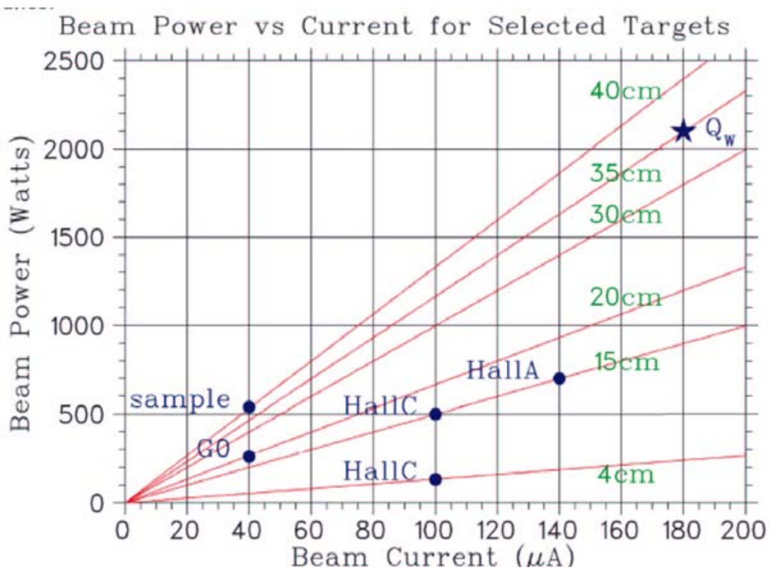
$\rightarrow$ requires survey accuracy ~ 1 mrad
(~ 1 mm for alignment of precision collimator with respect to target)

Auxiliary measurements (at low beam current) will be made with 1 set of GEMs and 2 pairs of Drift Chambers to:

- Measure shape of focal plane distribution.
- Measure position-dependent detector efficiency.
- Compared measured Q^2 distribution to Monte-Carlo

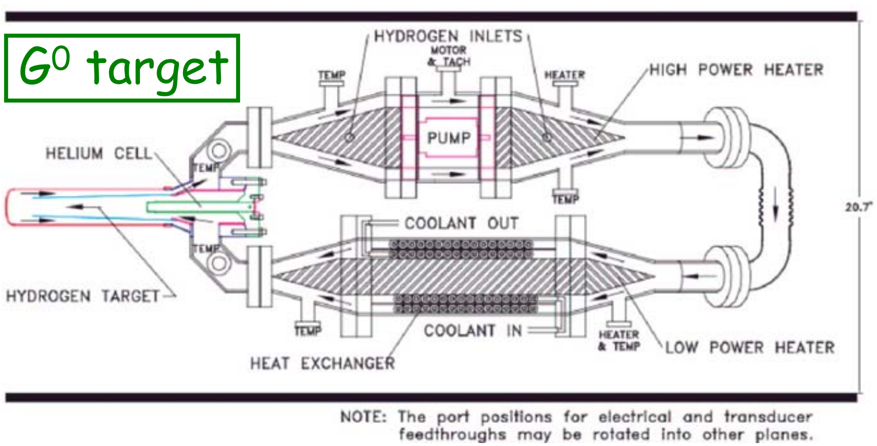


The Q^p_{weak} Liquid Hydrogen Target



Q^p_{Weak} Target parameters/requirements:

- Length = 35 cm
- Beam current = 180 μA
- Beam power = 2200 W
- Raster size ~4 mm x ~4 mm square
- Flow velocity > 700 cm/s
- Density fluctuations (at 15 Hz) < 5×10^{-5}



Target:

- Similar in design to SAMPLE and G^0 targets
  - → longitudinal liquid flow
  - → high stream velocity achieved with perforated, tapered "windsock"

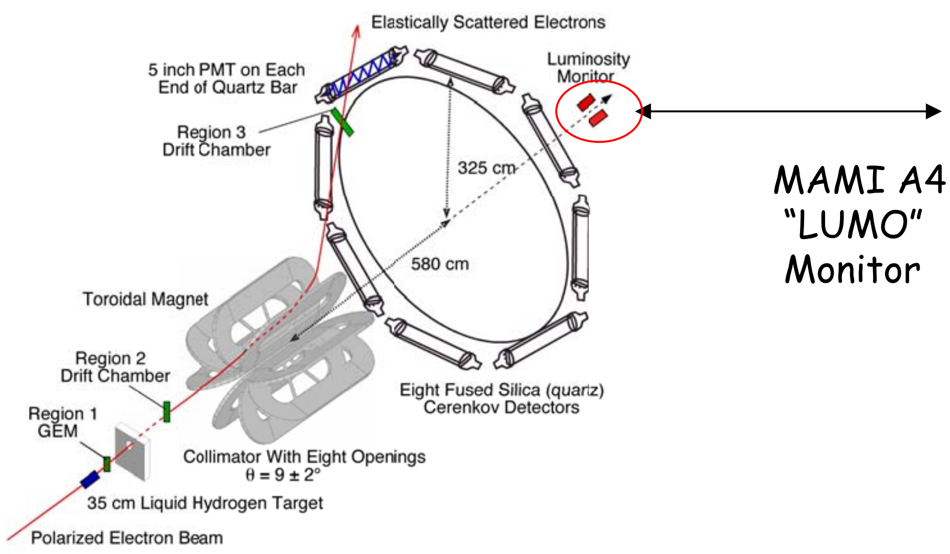
The Q^p_{weak} Luminosity Monitor

Luminosity monitor → Symmetric array of 8 Cerenkov detectors (quartz)
instrument with vacuum photo diodes & integrating readout
at small scattering angle $\theta \sim 0.8^\circ$ (low Q^2, high rates ~28 GHz/octant)

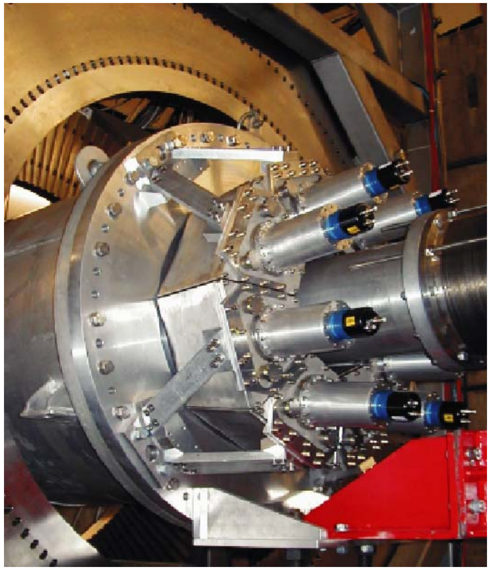
Expected signal components: 52% e-e Moller, 42% e-p elastic, 5% e-^{27}Al elastic.
Expected lumi monitor asymmetry « main detector asymmetry.
Expected lumi monitor statistical error ~ (1/6) main detector statistical error.

Useful for:

- Sensitive check on helicity-correlated beam parameter corrections procedure.
- Regress out target density fluctuations.



MAMI A4 "LUMO" Monitor



Summary and Outlook

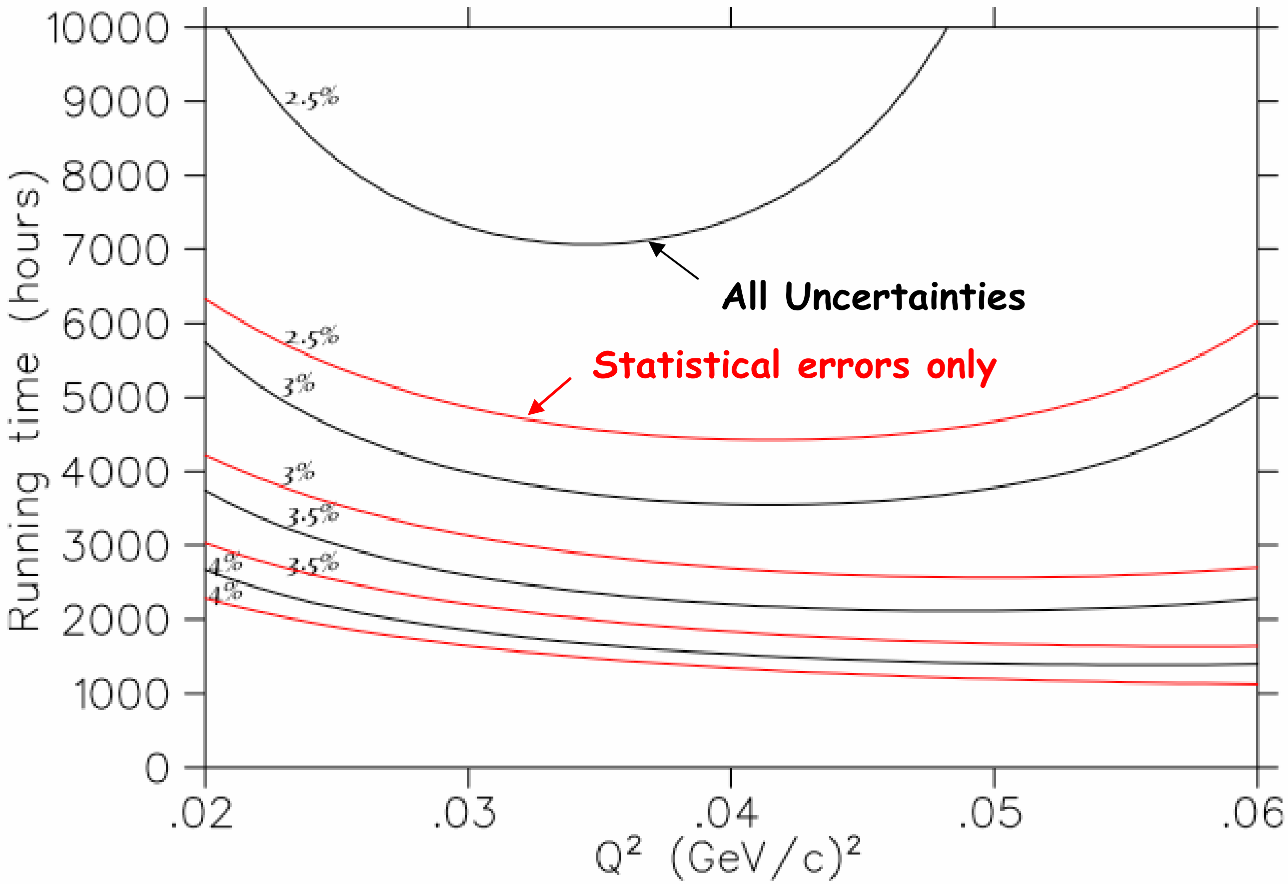
- Q_{weak} will provide a precision electroweak Standard Model test at low Q^2
- The sensitivity of our experiment to various Standard Model extensions complements that of existing or planned measurements in other systems.
- Capital funding is in place thanks to JLab/DOE, NSF, NSERC and university matching funds
- Magnet procurements placed in FY04 → installation in Hall C by 2007
- Since approval of the experiment, the scientific case has only gotten stronger; uncertainties in radiative corrections have been reduced by better calculations, and the allowed range for Leptoquark searches has increased somewhat (MJRM et al.) !

Go for it!

Thank you for inviting me to the sub Z workshop! ☺

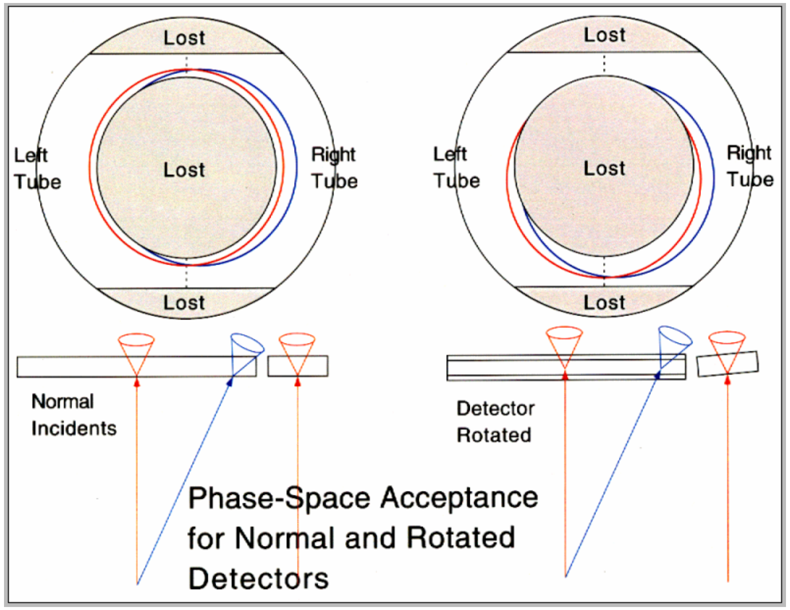
Can we do better than a 4% Qweak Measurement?

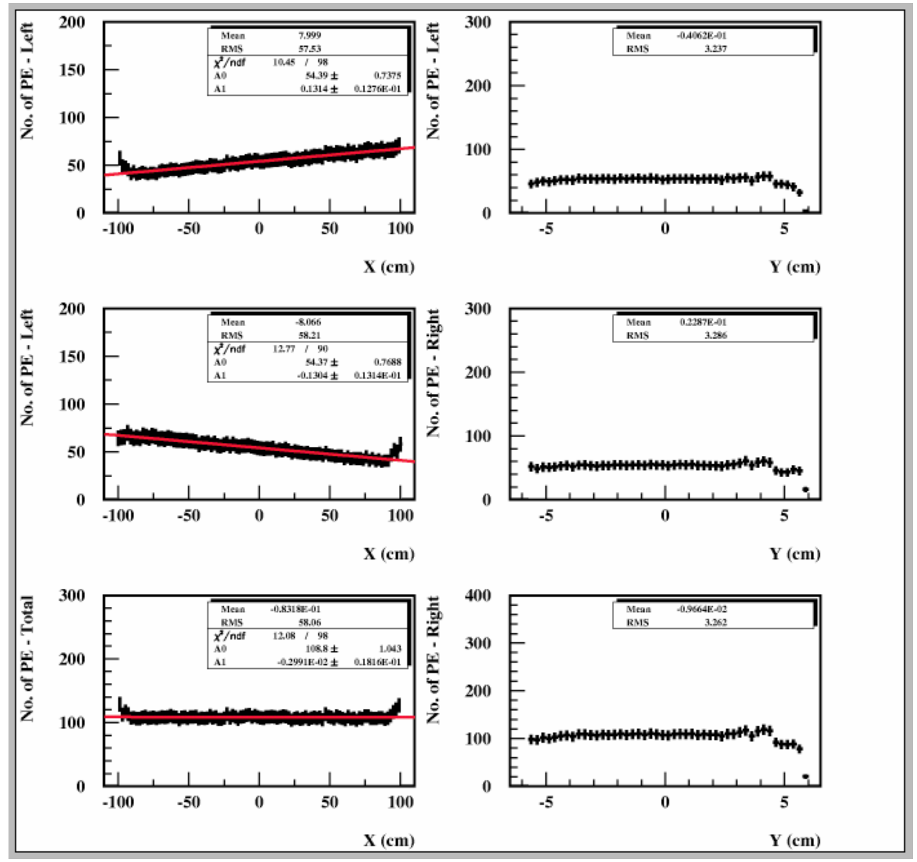
$\delta B = 2\%,\ \delta P = 0.5\%$



→ Must reduce systematic errors in polarization and hadronic background terms.

Uniformity of light collection in the Cerenkov bars:





Length

Width

12.5° Rotated Detector

Position dependence of the # of photoelectrons on each of the phototubes.

Simulation includes the full weighted cross-section and optics of the spectrometer.